Noname manuscript No.
(will be inserted by the editor)

High angular resolution imaging of the circumstellar material around intermediate mass (IM) stars

A. Fuente

Received: date / Accepted: date

Abstract In this Paper we present high angular resolution imaging of 3 intermediate-mass (IM) stars using the Plateau de Bure Interferometer (PdBI). In particular we present the chemical study we have carried out towards the IM hot core NGC 7129–FIRS 2. This is the first chemical study in an IM hot core and provides important hints to understand the dependence of the hot core chemistry on the stellar luminosity. We also present our high angular resolution (0.3") images of the borderline Class 0-Class I object IC1396 N. These images trace the warm region of this IM protostar with unprecedent detail (0.3"∼200 AU at the distance of IC1396 N) and provide the first detection of a cluster of IM hot cores. Finally, we present our interferometric continuum and spectroscopic images of the disk around the Herbig Be star R Mon. We have determined the kinematics and physical structure of the disk associated with this B0 star. The low spectral index derived from the dust emission as well as the flat geometry of the disk suggest a more rapid evolution of the disks associated with massive stars (see Poster by Alonso-Albi et al.). In the Discussion, we dare to propose a possible evolutionary sequence for the warm circumstellar material around IM stars.

Keywords stars: formation · stars: pre-main sequence: Herbig Be · stars: circumstellar disk · stars: individual (NGC 7129–FIRS 2, IC1396 N, R Monocerotis)

PACS 97.10.Bt · 97.21.+a · 98.62.Ai

A. Fuente
Observatorio Astronómico Nacional (OAN)
Apdo 112, E-28800 Alcalá de Henares, Spain
E-mail: a.fuente@oan.es

1 Introduction

Luminous intermediate-mass young stellar objects (IMs) (protostars and stars with $M_{*}\sim$5–10 $M_{\odot}$) are crucial in star formation studies. They share many characteristics with high-mass stars (clustering, PDRs) but their study presents an important advantage: there are many located closer to the Sun (d∼1 Kpc), and in regions less complex than massive star forming regions. Thus, they can be studied with high spatial resolution. The study of important problems of massive star formation like the physical and chemical structure of hot cores, clustering and the occurrence and physical properties of the disks around massive stars, requires of high spatial resolution. With the current instrumentation, these problems can only be addressed in IMs.

During the last 3 years, we have mapped a sample of IMs in different evolutionary stages using the Plateau de Bure Interferometer (PdBI). In particular we have detected and carried out a chemical study towards the IM hot core embedded in the Class 0 object NGC 7129–FIRS 2. Moving to more evolved objects, we have studied in detail the circumstellar disk associated with the Herbig Be star R Mon (see Poster by Alonso-Albi et al.). Finally, we have imaged the borderline Class 0-Class I object IC1396 N using the new A configuration of the PdBI which provides the highest angular resolution that can be achieved with the current millimeter instrumentation (0.3"∼200 AU at the distance of IC1396 N). These observations have allowed us to detect a cluster of hot core/corinos and have a first glance at the evolutionary stage of each cluster component. In this Paper, we revise the results obtained from these high spatial resolution studies and discuss the implications for the undestanding of the massive star formation process.

2 NGC 7129–FIRS 2

NGC 7129–FIRS 2 (hereafter, FIRS 2), with a luminosity $\sim 500\ L_\odot$ and a stellar mass $\sim 5\ M_\odot$, is very likely the youngest IM object known at present (Fuente et al. 2001,2005a). Recent PdBI observations in the continuum and spectroscopic lines carried out by our team show the existence of an IM hot core towards this young protostar (Fuente et al. 2005b). We estimate a size of 650×900 AU and a mass of $2\ M_\odot$ for the hot core associated with this object. The dimensions and mass of this IM hot core are intermediate between those measured in hot corinos (r$\sim$150 AU,M$<$1 $M_\odot$) and massive stars (r$\sim$3000 AU,M$>$10 $M_\odot$) and consequently, a differentiated chemistry is expected. This IM hot core provides a unique opportunity to study the dependence of the hot core chemistry on the stellar luminosity.

A large number of molecular lines have been detected in our interferometric spectra towards FIRS 2. Most of these lines are identified as belonging to deuterated (D_2CO, c-C_3D and c-C_3HD), sulphuretted (^{13}CS, OCS), and complex O-/N-bearing species (HCOOH, C_2H_5OH, C_2H_5CN). One chemical difference between hot corinos and hot cores is the enhanced abundance of deuterated species in the former. Loinard et al. (2003) searched for the doubly deuterated form of formaldehyde (D_2CO) in a large sample of young stellar objects. D_2CO was detected in all low-mass protostars with [D_2CO]/[H_2CO] ratios of 2–40%. On the other hand, no detection was obtained towards more massive protostars, where [D_2CO] [H_2CO]$<$0.5%. We estimate a [D_2CO]/[H_2CO]$\sim$0.14 towards the IM hot core FIRS 2. This value is 4 orders of magnitude larger than the cosmic D abundance and similar to those found in pre-stellar clumps and low-mass protostars.

The sulphuretted and complex compounds are characteristic of hot cores in both the low-mass and the high-mass regimes. We have compared the abundances of complex molecules in FIRS 2 with those in hot corinos and the massive hot cores OMC1 and G327.3–0.6. Contrary to model predictions, we did not detect any dependence of the O-/N-complex molecules ratio on the protostellar luminosity. However, we detected differences between the behavior of the O-bearing species with the stellar luminosity. While H_2CO and HCOOH are more abundant in low luminosity sources, CH_3OH seems to be more abundant in massive objects (see Fig. 1). Fuente et al. (2005b) proposed that this could be due to a different mantle composition in the two classes of region, caused by different physical conditions (mainly gas density and dust temperature) during the pre-stellar and accretion phase. However, this could also be due to other factors, such as the different spatial scale of the observations or a possible contribution of the shocked gas associated with the bipolar outflow to the emission of these molecules. The detection and detailed study of other intermediate-mass and low mass hot cores are necessary to establish firm conclusions.

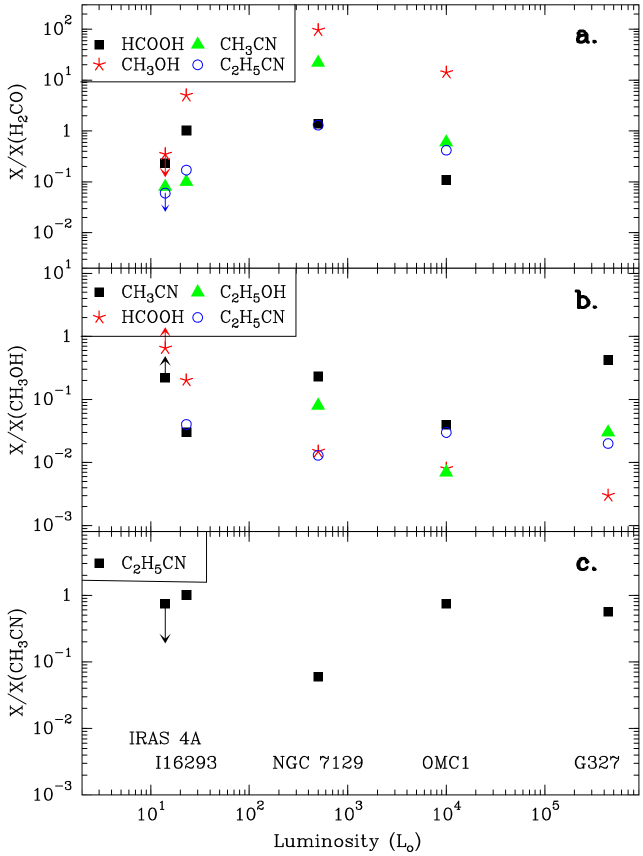

Fig. 1 Relative abundances of the complex O- and N-bearing molecules as a function of the protostellar luminosity for a sample of hot cores/corinos. Note that the HCOOH abundance seems to decrease with the protostellar luminosity (Fuente et al. 2005b).

3 R Mon

R Mon is the most massive disk detected in dust continuum emission at mm wavelengths around a Herbig Be star (Fuente et al. 2003). Moreover, it is the only one detected in molecular lines and thus far, our unique opportunity to investigate the physical structure and kinematics of the disks associated with these stars.

The high angular resolution continuum images at 2.7mm and 1.3mm reported by Fuente et al. (2006) allow us to determine the position (R.A.=06:39:09.954 Dec=+08:44:09.55 (J2000) and size ($\sim$150 AU) of the dusty disk. Moreover, by fitting the SED at cm and mm

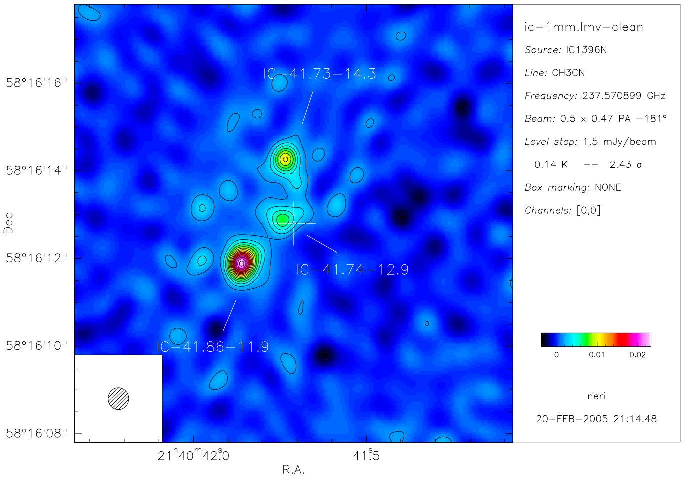

Fig. 2 Interferometric continuum image at 1.3mm obtained with the Plateau de Bure Interferometer (PdBI) towards the Class 0 protostar IC 1396N. A cluster of at least 3 hot cores cores is detected towards BIMA 2 (Neri et al. 2007).

wavelengths we determine a disk mass of 0.007 $M_\odot$ and β=0.3–0.5. Values of β between 0.5 and 1 are usually found in circumstellar disks around HAE and TTs and are thought to be evidence for grain growth in these disks (see e.g. Natta et al. 2006). The low value of β in R Mon suggests that grain growth has proceeded to very large sizes already in the short lifetime of its disk.

Alonso-Albi et al. report interferometric ^{12}CO and ^{13}CO observations towards this disk. They conclude that the disk is in Keplerian rotation around the star. Keplerian rotation has also been found in most of the TTs and Herbig Ae stars studied thus far and indicates a similar formation mechanisms for the stars in the range 1–8 $M_\odot$. However, contrary to the low mass T Tauri and Herbig Ae stars that are usually surrounded by flared disks, the observed ^{12}CO/^{13}CO intensity ratio in R Mon shows that the disk is geometrically flat (see Poster by Alonso-Albi et al.). This result is in line with previous near-IR and optical measurements that suggest that Herbig Be stars have geometrically flatter disks than Herbig Ae and T Tauri stars (see e.g. Meeus et al. 2001)

The flattening of the disk in Herbig Be stars can be due to the rapid grain growth. The grain growth causes the optical depth of the disk to drop and allows the UV radiation to penetrate deep into the circumstellar disk and photo-evaporate the disk external layers (Dullemond & Dominik 2004). Thus, we can propose an evolutionary sequence in which the disks associated with Herbig Be stars start with a flaring shape but become flat during the pre-main sequence and lose most of their mass (>90%) before the star becomes visible (<10^5 yr).

4 IC1396 N

The new A configuration of the PdBI allows us to study the warm interior of protostellar envelopes with unprecedent detail. In this Paper, we present interferometric continuum observations of the IM protostar IC1396 N (Neri et al. 2007).

IC1396 N is a 440 $L_\odot$ protostar located at a distance of 750 pc and Classified as a Class 0/I borderline source. Figure 2 shows the continuum image at 1.3mm. This image shows the presence of at least three bright continuum emission sources in the center of IC1396 N, all three associated with the source identified as BIMA 2 by Beltrán et al. (2002). The source BIMA 3 is also detected in our continuum image although lies outside the region shown in Figure 2. In addition to the 3 compact cores we detect some kind of extended emission in BIMA 2. In fact, the bulk of the mm-emission is emerging from a large region (∼3000 AU) centered on the triple-system. According to these results, we envision two different models for the continuum emission: (a) an envelope with sharp boundaries in which the three compact cores are embedded, (b) a region harboring a cluster of lower brightness cores from which we have detected the three most intense ones. The lack of sensitivity to large scale emission and emission distributed on a large number of cores makes it difficult to argue against one or the other model. For simplicity, we favor the model of the dusty 'cocoon' in which the three intense cores are embedded.

Neri et al. (2007) modeled the emission at 2.7mm and 1.3mm in the UV-plane assuming a 'cocoon+cores' structure. In Table 1 we show the fluxes and spectral indexes derived from this model. The weaker cores were not resolved by the interferometer. The primary core 41.86+13.2 is resolved in the 1.3mm emission to a size of ∼ 300 AU×150 AU, i.e. an order of magnitude larger than the size measured in hot corinos. This is consistent with this source being the precursor of a Herbig Ae/Be star. The 'cocoon' accounts for the 80% of the 1.3mm continuum emission and has a different spectral index from the compact cores. While the spectral index in the extended emission is ∼2.8 as expected for dust continuum emission with a standard value of β=1, the spectral indexes of the compact hot cores are all <2. We propose that this change in the spectral index is very likely associated with a change of the grain properties. The grains in the compact hot cores might be similar to those found in the evolved cirumstellar disks. In fact, the compact hot cores could be actually disks. We cannot discard, however, other possible interpretations for these small compact regions (see Neri et al. 2007 for a more detailed discussion).

Table 1 Millimeter flux densities, sizes, spectral indexes and masses

			3.3mm (91.7 GHz)		
	BIMA 3		BIMA 2		
		Cocoon	41.86+11.9	41.73+12.8	41.73+14.3
α (J2000)	21:40:42.84	21:40:41.86	21:40:41.85	21:40:41.73	21:40:41.72
δ (J2000)	58:16:01.4	58:16:13.2	58:16:11.9	58:16:12.8	58:16:14.3
Size (")	0.8 x 0.5	4.3 x 3.1	unresolved	unresolved	unresolved
S (mJy)	8	16	5.9	1.5	2.7
			1.3mm (237.6 GHz)		
	BIMA 3		BIMA 2		
		Cocoon	41.86+11.9	41.73+12.8	41.73+14.3
α (J2000)	21:40:42.84	21:40:41.85	21:40:41.86	21:40:41.73	21:40:41.73
δ (J2000)	58:16:01.4	58:16:13.1	58:16:11.9	58:16:12.8	58:16:14.3
Size (")	0.8 x 0.4	4.5 x 3.1	0.4 x 0.2	unresolved	unresolved
S (mJy)	30	245	35	6	10
	BIMA 3		BIMA 2		
		Cocoon	41.86+11.9	41.73+12.8	41.73+14.3
Mean Spec.Index	1.4		2.6		
Spec.Index	1.4	2.8	1.9	1.5	1.4
Mass ($M_\odot$)	0.05	0.4	0.06	0.01	0.01
β	$\leq$0	$\sim$1.0			

5 Summary and Discussion

A major interest in the Astrophysics today is the understanding of hot cores. These warm regions in the interior of the protostellar envelopes are the prime material from which the proto-planetary disks are formed. However the detailed physical and chemical structure of these hot regions as well as their evolution to become proto-planetary disks are not known. High spatial resolution imaging of the warm regions of protostellar objects is required to have a deeper insight into this problem.

In this Paper we present high angular resolution imaging of 3 IMs using the Plateau de Bure Interferometer (PdBI). These stars are thought to be in a different evolutionary stage. NGC 7129–FIRS 2 is a young Class 0 object hosting a massive ($\sim$2 $M_\odot$) and compact hot core. IC1396 N is a borderline Class 0-Class I object. Our interferometic images reveal a massive 'cocoon' in which three compact cores are embedded. R Mon is a visible star surrounded by a circumstellar disk. We can propose a simple evolutionary scheme in which a IM star starts its life surrounded by a massive and dense hot core. The newly formed star(s) disperses part of the hot core material producing a less dense 'cocoon' in which the circumstellar disks are immersed. At this stage, the density contrast between the 'cocoon' and the molecular cloud is still high enough for the cocoon to be detected with the interferometer. Finally the cocoon is dispersed and only the circumstellar disk is left. Of course, this is only a rough description of what the evolution of the warm circumstellar material could be and future interferometric observations are needed to confirm and extend this scheme.

Acknowledgements This work has been partially supported by the Spanish MEC and Feder funds under grant ESP2003-04957 and by SEPCT/MEC under grants AYA2003-07584.

References

Beltrán, M. T., Girart, J. M., Estalella, R., Ho, P. T. P., & Palau, A.: *ApJ*, 573, 246 (2002)

Dullemond, C. P., & Dominik, C.: A&A 417, 159 (2004)

Fuente, A., Rodríguez-Franco, A., Testi, L., Natta, A., Bachiller, R., Neri, R: ApJL 598, L39 (2003)

Fuente, A., Rizzo, J. R., Caselli, P., Bachiller, R., & Henkel, C. *A&A*, 433, 535 (2005a)

Fuente, A., Neri, R., & Caselli, P.: *A&A*, 444, 481 (2005b)

Fuente, A., Alonso-Albi, T., Bachiller, R., Natta, A., Testi, L., Neri, R., & Planesas, P.: *ApJ*, 649, L119 (2006)

Loinard, L., et al.: SFChem 2002: Chemistry as a Diagnostic of Star Formation, p. 351, eds Charles L. Curry and Michel Fich. NRC Press, Ottawa, Canada (2003)

Meeus, G., Waters, L. B. F. M., Bouwman, J., van den Ancker, M. E., Waelkens, C., & Malfait, K.: *A&A*, 365, 476 (2001)

Natta, A., Testi, L., Calvet, N., Henning, T., Waters, R., Wilner, D.: in Protostars and Planets V, p. 767, eds B. Reipurth, D. Jewitt, and K. Keil, University of Arizona Press, Tucson (2007)

Neri, R., Fuente, A., Ceccarelli, C., Caselli, P., Johnstone, D., van Dishoeck, E., Wyrowski, F. et al.: 2007, arXiv:0705.2663